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APOLLO 11 ENTRY POSTFLIGHT ANALYSIS

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LANDING ANALYSIS BRANCH
MISSION PLANNING AND ANALYSIS DIVISION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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PROJECT APOLLO

APOLLO 11 ENTRY POSTFLIGHT ANALYSIS

By R. Manders
Guided Entry
TRW Systems Group

February 20, 1970

MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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APOLLO 11 ENTRY POSTFLIGHT ANALYSIS

By Robert H. Manders
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1. SUMMARY

This report presents the postflight evaluation of the operation of the Apollo 11 Command Module Computer (CMC) and associated systems during the entry phase of the Apollo 11 mission. The emphasis of this report is placed on the operation of the Command Module Computer (CMC), the Entry Monitor System (EMS), and an evaluation of the entry monitoring procedures as defined for the Apollo 11 entry phase. Evaluation of the CMC was complicated by the lack of inflight telemetry (TM) data. The only data available for use in the analysis was a scattering of downlink data picked up by ARIA aircraft, recovery operations data, and the EMS scroll pattern. The analysis has shown that the CMC performed properly throughout the entry phase. The onboard CMC-computed position at touchdown was 169.15 degrees west longitude and 13.30 degrees north latitude, approximately 1.7 nautical miles from the planned touchdown point. The simulated CMC position at touchdown was 169.14 degrees west longitude and 13.34 degrees north latitude.

Reconstruction of the actual environment was obtained through the use of the EMS scroll pattern trace and the onboard CMC solution for the onboard reference trajectories at exit from the Huntest phase as recorded by the ARIA aircraft. This reconstruction indicates that the entry flight path angle from the 21-day best estimate trajectory (BET) is different from the entry flight path angle which best fits all available data for the Apollo 11 entry phase.

An evaluation of the recommended entry monitoring procedures indicates that the procedures were followed by the crew and all critical tests performed by the crew prior to and during the entry phase were successful and truly indicated the status of the entry onboard systems.

This report has been prepared as a Supplement 10 to the Apollo 11 Mission Report (MSC - 00171).

2. INTRODUCTION

2.1 Purpose

The primary objective of this report is to present an evaluation of the Apollo 11 entry guidance, navigation, and control system (GNCS). Secondly, a reconstruction of the entry environment utilizing the entry monitor system (EMS) scroll pattern trace and downlink data obtained by ARIA aircraft is presented. No entry telemetry (TM) data was available from the Apollo 11 mission. Thirdly, an evaluation of the Apollo entry monitoring procedures is presented. This work was performed according to the agreement in Reference 1.

2.2 General Description of Contents

This report is broken into four areas of interest: Entry Conditions, Environment Reconstruction, CMC Evaluation, and Evaluation of Entry Monitoring procedures. The content of each section is described below:

Section 3 presents the entry state vectors utilized in the reconstruction. The final reentry state vector from the Real Time Computing Complex (RTCC) called CROX880 was utilized for the CMC while a modified version of the 21-day BET entry state vector was utilized in the environment reconstruction.

Section 4, which describes the environment reconstruction, presents the CM aerodynamics, atmosphere model and CM mass properties used to perform the analysis. Trajectory parameters from the reconstruction are presented. The differences between the 21-day BET entry state vector and the vector utilized to obtain the best entry trajectory data fit are presented.

Section 5 discusses the operation of the CMC during the entry phase of Apollo 11. Since no TM data is available the program sequencing and the discussion of the significant events presented are from the reconstructed trajectory. The reference trajectory data calculated by the CMC and recorded by the ARIA aircraft are compared to the reconstruction.

Also discussed in Section 5 is a summary of the EMS operation.

Described in Section 6 are the entry monitoring procedures utilized for the Apollo 11 mission. These procedures are evaluated from the standpoint of the flight crew utilization and the performance of the entry monitoring procedures for the specific case of the Apollo 11 entry.

3. ENTRY CONDITIONS

The entry state vectors used for the Apollo 11 postflight analysis were obtained from two sources: the RTCC CROX880 state vector and the 21-day BET.

The BET indicates that the Apollo 11 command module entered the earth's atmosphere, defined at a geodetic altitude of 400,000 feet, at 195 hours 03 minutes 05.66 seconds after liftoff. The entry state vector obtained from the BET at this time is as follows:

Inertial velocity	36,194.368 ft/sec
Inertial flight path angle	-6.48 deg
Inertial azimuth	50.1761 deg
Longitude	171.9603 deg East
Geodetic Latitude	3.1933 deg South
Geodetic Altitude	400,000.72 ft

The entry state vector on board the CMC was based on the RTCC CROX880 vector. The vector corresponding to this time was slightly different from the BET state vector. It is as follows:

Inertial velocity	36,195.287 ft/sec
Inertial flight path angle	-6.4875 deg
Inertial azimuth	50.1823 deg
Longitude	171.9622 deg East
Geodetic Latitude	3.1968 deg South
Geodetic Altitude	398,867.97 ft

The analysis was performed utilizing the above state vectors; the CMC simulation was initialized with the RTCC vector and the environment was initialized with the 21-day BET vector. Unsatisfactory results were obtained. The maximum-g experienced during the initial atmospheric penetration as recorded on the EMS scroll pattern could not be achieved with the above conditions. Also an adequate reconstruction of the GNCS reference trajectory solution at termination of the Huntest Phase could not be obtained.

It has been found, as a result of this analysis, that the following entry state vector is a better estimate of entry conditions than the 21-day BET:

Inertial velocity	36,194.368 ft/sec
Inertial flight path angle	-6.5230 deg
Inertial azimuth	50.1761 deg
Longitude	171.1960 deg East
Geodetic Latitude	3.1933 deg South
Geodetic Altitude	400,000.72 ft

This state vector is -0.043 degree in flight path angle different from the BET and when utilized for environment initialization, results in an excellent reconstruction of the entry trajectory flown by the Apollo 11 CM.

4. ENVIRONMENT RECONSTRUCTION

The reconstructed entry environment is presented in this section and compared to the EMS scroll pattern trace. Due to the lack of TM data, this is the only source of comparison available. The entry parameters that were varied to match this trace were the CM aerodynamics, the atmosphere model, and the entry flight path angle. The CM weight used was the pre-entry estimated value of 12,148 pounds and was held fixed during the analysis.

The Apollo 11 entry trajectory was reconstructed utilizing the six-degree-of-freedom option of the Apollo Reentry Simulation (ARS) (Reference 2).

The selection of the proper entry parameters was based on the best overall comparison of the following: (1) first maximum load factor and velocity at that point; (2) first minimum load factor and velocity at that point; (3) second maximum load factor and velocity at that point; (4) touchdown point; and (5) the best match of the actual to reconstructed EMS pattern.

4.1 Entry Parameters

The entry state vector utilized to initialize the CMC was the RTCC vector based on CROX880. The vector utilized the initialize the environment was based on the 21-day BET. These vectors may be found in Section 3. Utilizing these conditions, it was found that no reasonable combination of atmosphere and aerodynamics would yield a satisfactory reconstruction of the Apollo 11 entry. An adjustment of -0.043 degrees was made in the entry flight path angle to the 21-day BET state vector and a satisfactory entry reconstruction was obtained. The following data will indicate the closeness of the reconstruction:

	Actual Apollo 11	Reconstructed Apollo 11
First maximum load factor	6.73 g	6.74 g
Velocity at first maximum load factor	31,810 ft/sec	31,776 ft/sec
First minimum load factor	0.48 g	0.60 g
Velocity at first minimum load factor	20,500 ft/sec	20,257 ft/sec
Second maximum load factor	6.00 g	6.00 g
Velocity at second maximum load factor	12,390 ft/sec	13,070 ft/sec

The actual Apollo 11 data was obtained from the EMS scroll pattern and the reconstructed data is EMS velocity and EMS load factor from the ARS CMC simulation.

The reconstructed aerodynamics, Figure 1, correspond to a hypersonic ($M > 29.5$) CM lift-to-drag (L/D) ratio of 0.282. This aerodynamic data fits the limited flight data obtained by the ARIA aircraft. The atmospheric model which yielded best results was the 30 degree North Latitude January atmosphere (Reference 3). Utilizing the state vectors from Section 3 and the aerodynamic and atmosphere described above results in the best reconstructed trajectory obtainable with the data available. Pertinent trajectory time histories are presented in Figures 2 through 6. The reconstructed trajectory touchdown point is at 169.14 degrees west longitude and 13.34 degrees North latitude or approximately 1.80 nautical miles from the planned touchdown target (Figure 8). The difference in crossrange between actual CMC and simulated CMC can be contributed to the Lateral Logic Deadband.

5. CMC EVALUATION

The purpose of this section is to present an evaluation of the Apollo 11 GNCS system. A description of the guidance system's operation with respect to various trajectory parameters and terminal objectives is presented. The available inflight CMC data recorded by the ARIA aircraft is then compared to the reconstructed CMC data.

5.1 Description of CMC Operation

The Apollo 11 entry consisted of four phases: entry initialization and attitude hold (Program 63), post 0.05g (Program 64), UPCONTROL (Program 65), and FINAL PHASE (Program 67). Programs 61 and 62 operated correctly and sequenced to Program 63 at the proper time. The CMC remained in Program 63 until the edge of the sensible atmosphere (0.05g) was reached. At this point atmospheric guidance began. Once the computed drag level, KA, was reached, a constant drag level, DO, was flown until the predicted range to target (HUNTEST Phase) was within 25 nautical miles of the actual range to go ($|DIFF| \leq 25$). The UPCONTROL phase (Program 65) was entered at this point and was flown until the predicted value of drag to terminate UPCONTROL (DL) was reached and the guidance transferred to FINAL PHASE (Program 67). The trajectory flown in FINAL PHASE resulted in a touchdown at 13.30 degrees north latitude and 169.15 degrees west longitude or approximately 1.7 nautical miles from the planned touchdown point. No data is available on the actual CMC sequencing. Figure 7 presents the reconstructed CMC sequencing and the respective touchdown points are presented in Figure 8. The reconstructed CMC was obtained from the six-degree-of-freedom version of the ARS program utilizing the guidance logic. All discussions which follow on the trajectory events will reflect the reconstructed CMC.

5.1.1 Entry Initialization and Attitude Hold (Program 63).- The guidance system was initiated with the proper switches and control constants in Program 63. At a geodetic altitude of 398,867.97 feet, the simulated CMC computed an inertial velocity of 36,195.29 feet per second and an inertial flight path angle of -6.488 degrees. The ground elapsed time from liftoff to entry interface was 195 hours 03 minutes 05.7 seconds. The entry point was located at a geodetic latitude of 23.193 degrees south and a longitude of 171.196 degrees east which resulted in a relative range of 1497 nautical miles and an inertial range of 1585 nautical miles. Onset of 0.05g occurred 30 seconds after entry at a geodetic altitude of 289,926 feet. The simulated CMC then calculated the reference drag level for the constant drag logic, DO, and the command module's position in the entry corridor relative to the lift vector orientation line. The values of KA and DO, based on the inertial velocity at 0.05g, were 1.418g's and 3.991g's respectively, while the commanded bank angle was zero degrees.

5.1.2 Post 0.05g (Program 64).- The simulated CMC then sequenced to program 64 at 0.05g. The lift-up attitude commanded at the end of program 63 was maintained until the drag level became greater than 1.426g's, 52 seconds after entry, at which time the guidance system began the constant drag portion of the trajectory.

The L/D control equation in the constant drag logic is driven by drag and altitude rate errors based on a computed reference trajectory. Initially the commanded bank angle was zero degrees (Lift vector up) (See Figure 9) due to the large negative altitude rate. The reconstructed altitude rate became less negative than -700 ft/sec 78 seconds after entry (See Figure 2) and the simulated guidance system began ranging predictions. The reconstructed inertial range to the target at this time was 1122 nautical miles (See Figure 3). Due to the large energy level of the command module, an overshoot trajectory was predicted, hence the guidance system remained in the constant drag logic. The maximum load factor, 6.73g's, occurred 82 seconds after entry and the first minimum altitude (See Figure 4), 182,109 feet, occurred 88 seconds after entry. When the load factor dropped below 5.44g's the guidance system properly commanded a bank angle of -180 degrees.

The guidance remained in the HUNTEST/CONSTANT DRAG logic until the energy level was decreased to allow the definition of a successful reference trajectory (predicted range to target within 25 nautical miles of actual range to target). This reference trajectory is shown in Table I and is compared to the actual (obtained from ARIA data).

5.1.3 UPCONTROL Phase (Program 65).- With the definition of the reference trajectory 118 seconds after entry control transferred to the UPCONTROL phase. The actual velocity, altitude rate, and acceleration at the time of transfer were 26,832.5 ft/sec, 75.26 ft/sec, and 3.405g, respectively.

The UPCONTROL reference trajectory is defined based on four quantities: acceleration at pullout (AO), velocity at pullout (V1), acceleration at UPCONTROL termination (DL), and velocity at UPCONTROL termination (VL). The values of AO, V1, DL, and VL were 3.176g, 26,334.2 ft/sec, 1.057g, and 22,090.8 ft/sec, respectively. These data were obtained from ARIA data and are compared to the reconstructed trajectory in Table I.

The reconstructed guidance flew the UPCONTROL reference trajectory and achieved the value DL 200 seconds after entry with a velocity of 21,311.4 ft/sec.

5.1.4 FINAL PHASE (Program 67).- The reconstructed guidance system sequenced to the final phase logic when the inertial velocity was 21,301 ft/sec (See Figure 7); the altitude rate was 306 feet per second. The CM was in a lift-up attitude and the inertial range to the target was 615 nautical miles. The first range prediction in FINAL PHASE resulted in a predicted downrange error of 23 nautical miles. The predicted downrange error then

increased to a 30 nautical mile undershoot at 216 seconds after entry. The predicted downrange error was increased to a 29 nautical mile overshoot at 260 seconds after entry. The predicted downrange error remained positive (overshoot) until the inertial velocity became less than 12,833 feet per second, 381 seconds after entry. At this point the guidance system began utilizing relative velocity in the range predictions in place of the inertial velocity. During simulated FINAL PHASE the altitude reached a relative maximum of 220,072 feet, 256 seconds after entry, while the load factor decreased to a relative minimum of 0.60g, 262 seconds after entry. The load factor increased to a second maximum of 5.98g, 374 seconds after entry. The overall trajectory flown in final phase was at an average bank angle of 70 degrees and resulted in a touchdown at a geodetic latitude of 13.300 degrees north and a longitude of 169.150 degrees west, 1.69 nautical miles from the target, as shown in Figure 8.

Three lateral switches occurred during simulated FINAL PHASE. A lateral switch occurs whenever the crossrange deadband is exceeded. Crossrange deadband is computed by the guidance and is proportional to the spacecraft's lateral ranging capability at its current velocity. If the roll command is within ±15 degrees of full lift up or down, the deadband is halved to account for the smaller lateral force. The lateral switches occurred at 376 seconds, 436 seconds, and 468 seconds after entry, as indicated in Figure 10.

5.2 CMC Simulation

A computer simulation of the CMC operation during entry was made. The entry parameters obtained from the simulation were then compared to those recorded by ARIA aircraft.

5.2.1 Simulation.- The computer simulation of the CMC operation was made with the Apollo Reentry Simulation (ARS) program utilizing six-degree-of freedom. The simulated CMC was initialized with the entry state vector obtained from the RTCC vector CROX 880 at a ground elapsed time of 195 hours 03 minutes and 05.66 seconds. The environment was initialized utilizing the modified 21-day BET vector as discussed in Section 3.

5.2.2 Comparison.- The results obtained from the simulation (simulated CMC) were compared to the CMC computations recorded by the ARIA and were in close agreement. The actual CMC data is not available as a function of time and therefore no time history comparisons are made herein. Due to the lack of TM data, the program sequencing obtained from the simulated CMC is presented as that of the actual CMC. These reconstructed data are shown in Figures 2 through 6 and in Tables I and II.

Table II presents a comparison between the actual and the reconstructed conditions at reference trajectory solution (termination of HUNTEST Phase, P-64). The actual conditions were obtained by solving the following equations simultaneously for velocity, altitude rate, and acceleration:

$$\text{ASPDWN} = (-\text{RDOT})(\text{V})(\text{ATK})/[(\text{AO})(\text{LAD})(\text{RE})] \tag{1}$$

$$\text{V1} = \text{V} + \frac{\text{RDOT}}{\text{LEWD}} \tag{2}$$

$$\text{AO} = \left(\frac{\text{V1}}{\text{V}}\right)^2 \text{D} + \text{RDOT}^2/[(2)(\text{C1})(\text{HS})(\text{LEWD})] \tag{3}$$

The quantities ASPDWN, V1, AO, and LEWD are data obtained from the ARIA downlink and LAD, C1, HS, RE, and ATK are input guidance constants. The data calculated in this manner shows good agreement with the reconstructed data and indicates the CMC correctly computed the reference trajectory data. Data is presented at ±2 seconds from the time of solution to illustrate the closeness of the reconstruction.

5.3 EMS Reconstruction

The Apollo 11 EMS scroll is shown in Figure 11. The EMS acted satisfactorily. No incompatibilities occurred and it offered an adequate monitor.

The reconstructed EMS is based on the EMS output data from the six-degree-of-freedom entry reconstruction.

6. EVALUATION OF THE ENTRY OPERATIONS AND MONITORING PLAN

This section provides a chronological sequence of events of crew operations while monitoring entry. The data presented is from the onboard telemetry tape prior to the entry interface and from the ARIA aircraft and the reconstructed trajectory following entry interface. The data indicates what the crew observed real time and how they responded in the process of monitoring entry. Table III presents the Apollo 11 sequence of events in addition to PAD data necessary to monitor the onboard computer.

6.1 Entry Monitoring Plan Prior to Entry Interface

An additional horizon monitor check was performed at Entry Interface minus 30 minutes (EI - 30). The pitch gimbal angle (PGA) from the entry PAD (Figure 12) matched exactly with the actual at the time of the check. Horizon tracking was initiated by the command pilot at EI - 30 minutes.

Program 61 was initiated 19 minutes prior to EI. The first DSKY display in Program 61 displayed the target latitude and longitude and lift vector orientation (LVO). The target latitude was 13.32 degrees north and longitude was 169.17 degrees west; the actual splashdown coordinates were 13.30 degrees north and 169.15 degrees west. The LVO was displayed in the up orientation. The second DSKY display displayed predicted values of GMAX = 6.46g's, velocity at EI = 36,184 ft/sec and flight path angle at EI = -6.46 degrees. These values compared to the actual conditions of GMAX = 6.73g's, velocity (EI) = 36,194 ft/sec, and flight path angle (EI) = -6.52 degrees. The final DSKY display of P61 displayed the predicted inertial range to the target at 0.05g = 1418 nautical miles, predicted velocity at 0.05g = 36,261 ft/sec, and predicted time of 0.05g = EI + 28 seconds. The actual value of inertial range to target at 0.05g was 1418 nautical miles and inertial velocity at 0.05g was 36,275 ft/sec. These values compared favorably. The reconstructed time of 0.05g occurred as predicted.

Program 62 was entered at EI - 16 minutes. The request for separation appeared immediately; consequently, the IMU was neither reversed nor unsatisfactory. At EI - 14 minutes, the pitch gimbal angle check was performed. The pitch gimbal angle was well within the allowable five degree tolerance.

CM/SM separation occurred at EI - 13 minutes, 49 seconds. The command pilot waited after separation to insure adequate separation distance before maneuvering. The DSKY display of target coordinates then appeared with the lift vector orientation for entry. The values were the same as in P61. The DSKY display of desired gimbal angles then appeared: Roll = 0.1 degree, Pitch = 175.0 degrees, and Yaw = .9 degree. The DSKY display of desired gimbal angles was displayed until EI - 7 minutes, 01 seconds; at this time

program 63 automatically sequenced in. The DSKY display of load factor = 0.0g, inertial velocity = 33,258 ft/sec, and range to go = 3732 nautical miles appeared. The load factor remained constant until after entry interface, the inertial velocity increased to 36,277 ft/sec and then decreased from this point, and the range to go naturally decreased throughout entry.

The crew reported that the moon entered the field of view at EI - 4 minutes as predicted.

6.2 Entry Operations and Monitoring After Entry Interface

Due to the lack of TM data, this section will be based on the reconstructed trajectory.

The occurrence of 0.05g was within the 2 second computer interval of the predicted time. Program 64 and the entry monitor system sequenced in immediately. At EI + 30 seconds, the first P64 DSKY display of bank angle command = -15.2 degrees, inertial velocity = 36,277 ft/sec, and altitude rate = -3186 ft/sec was available. The Huntest phase of the entry guidance was entered at EI + 1 minute 18 seconds. At EI + 1 minute 30 seconds the first roll command other than 0 or 15.2 degrees was issued. At EI + 1 minute 56 seconds the entry guidance solved for a successful set of reference trajectories and entered Program 65. The values of VL = 22,091 ft/sec and DL = 1.057g's displayed were well within the tolerances passed on the Entry Pad (Figure 12).

The entry pad value of the time of V_{CIRC} was EI + 2 minutes, 14 seconds. At this time the actual velocity of the vehicle was 24,983 ft/sec. The actual time of V_{CIRC} occurred at EI + 2 minutes, 06 seconds. At EI + 3 minutes 20 seconds the guidance entered P67. The first simulated DSKY display during P67 indicated an undershoot of 132 nautical miles. With the most critical portion of entry successfully negotiated, ranging to the target and avoiding high g loads is the primary concern. At EI + 6 minutes and 04 seconds, the simulated DSKY display of RTOGO = 1.7 (undershoot), present latitude = 13.30 degrees north and present longitude = 169.15 degrees west indicates that the target was achieved by the guidance system. The drogue chutes were deployed at EI + 9 minutes and 13 seconds and the main chutes were deployed approximately 50 seconds later.

Table I. Comparison Of The Actual CMC And Simulated CMC Reference Trajectory Data

Variable	Actual CMC	Reconstructed CMC
Predicted Velocity at CM Pullout, C1 (ft/sec)	26,334	26,601
Predicted Acceleration at CM Pullout, AO (g)	3.176	3.521
Predicted Velocity at Termination of UPCONTROL, VL (ft/sec)	22,090	22,038
Predicted Acceleration at Termination of UPCONTROL, DL (g)	1.057	1.054
Predicted Range to CM Pullout, ASPDN (n. mi.)	-11.87	-20.48
Predicted Range to be Flown During UPCONTROL, ASPUP (n. mi.)	181.934	193.890
Predicted Range to be Flown During KEPLER, ASKEP (n. mi.)	0	0
Predicted Range to be Flown During FINAL PHASE, ASP1 (n. mi.)	528.662	525.667
Predicted Gamma Correction to FINAL PHASE Range, ASP3 (n. mi.)	246.05	246.05
Total Range Prediction, ASP (n. mi.)	945.775	945.118
Reference L/D for UPCONTROL, LEWD	0.15	0.15

Table II. Comparison Of CMC Conditions At Termination Of HUNTEST Phase

Quantity	Actual CMC	Reconstructed CMC
		*T - 2 - 26,837
Inertial Velocity, VI (ft/sec)	26,832	26,635
		*T + 2 - 26,439
		*T - 2 - 178.09
Altitude Rate, RDOT (ft/sec)	75.26	122.22
		*T + 2 - 67.11
		*T - 2 - 3.308
Total Acceleration, D (g)	3.045	3.217
		*T + 2 - 3.143

* T - 2 is the state 2 seconds (1 computer cycle) prior to HUNTEST termination and T + 2 is the state 2 seconds after HUNTEST termination from the reconstruction.

Table III. The Chronological Sequence of Events of the Apollo 11 Entry and Available Pad Data Necessary to Monitoring Entry

APOLLO 11 MISSION EVENT TIME	APOLLO 11 EVENT	REAL TIME DATA PROVIDED TO CREW	COMMENTS
EI - 30 min	Pitch Gimbal Angle (PGA) Check is performed PGA = 298.0 deg	PAD PGA = 298.0 deg	The actual value of the PGA is sufficiently close to the PAD value to successfully pass the monitoring plan test.
EI - 19 min P61	P61 was initiated	Initiated P61 at EI - 19 min	
P61	V06 - N61 DSKY DISPLAY Target Latitude = 13.32 deg, Target Longitude = -169.17 deg, Lift Vector Up	Target Latitude = -13.32 deg Target Longitude = -169.17 deg Lift Vector Up	
P61	V06 - N60 DSKY DISPLAY pred. GMAX = 6.46g, pred. velocity (EI) = 36184 ft/sec, pred. flight path angle (EI) = -6.46 deg	Pred. GMAX = 6.30g Pred. Velocity (EI) = 36194 ft/sec Pred. Flight Path = -6.48 deg	
P61	V06 - N63 DSKY DISPLAY pred. RTOGO (0.05g) = 1418 n mi Pred. Velocity (0.05g) = 36269 ft/sec; Pred. Time to 0.05g = EI + 28 sec	Pred. RTOGO (0.05g) = 1403 n mi Pred. Velocity (0.05g) = 36275 ft/sec Pred. Time to 0.05g = EI + 28 sec	
EI - 16 min P62	P62 is entered	Initiate P62 at EI - 18 min	V25-N50 is flashing Request. separation

Table III. The Chronological Sequence of Events of the Apollo 11 Entry and Available Pad Data Necessary to Monitoring Entry (Continued)

APOLLO 11 MISSION EVENT TIME	APOLLO 11 EVENT	REAL TIME DATA PROVIDED TO CREW	COMMENTS
EI - 13 min 49 sec (P62)	CM/SM separation occurred	CM/SM separation at EI - 15 min	
P62	V06 - N61 DSKY DISPLAY The same values as for P61 display		Last chance to update target
P62	V06 - N22 DSKY DISPLAY Roll Gimbal Angle = 0.1 deg Pitch Gimbal Angle = 175.0 deg Yaw Gimbal Angle = .9 deg		
EI - 7 min 01 sec (P63)	P63 automatically sequenced in		
P63	V06 - N64 DSKY DISPLAY Load factor = 0.0g Inertial velocity = 33,258 ft/sec RTOGO = 3732 n mi		
EI - 30 min TO EI	Crew tracked horizon on 31.7 deg window mark	Crew provided two options: 1) Maintain 0.05g attitude 2) Track horizon on 31.7 deg mark on window	Pitch error needle will indicate proper functioning of G&N prior to entry

Table III. The Chronological Sequence of Events of the Apollo 11 Entry and Available Pad Data Necessary to Monitoring Entry (Continued)

APOLLO 11 MISSION EVENT TIME	APOLLO 11 EVENT	REAL TIME DATA PROVIDED TO CREW	COMMENTS
EI (P63)	Load factor = 0.0g Inertial velocity = 36190 ft/sec RTOGO = 1593.0 n mi	Inertial velocity = 36194 ft/sec	
EI + 0 min 28 sec (P63)	Load factor = 0.049g Inertial velocity = 36276 ft/sec RTOGO = 1418 n mi	Load factor = 0.05g Inertial velocity = 36275 ft/sec RTOGO = 1403 n mi	
EI + 0 min 30 sec	P64 sequenced in V06 - N68 DSKY DISPLAY Bank angle command = 0.0 deg Inertial velocity = 36277 ft/sec Altitude rate = -3186 ft/sec	Bank angle command = 0.0 deg Inertial velocity = 36277 ft/sec	
EI + 1 min 18 sec (P64)	Huntest phase entered RDOT = -666 ft/sec		
EI + 1 min 30 sec (P64)	First non-zero bank command Inertial velocity 30176 ft/sec RDOT = 211 ft/sec Bank angle command = 54.43 deg		
EI + 1 min 56 sec (P65)	P65 sequenced in V16 - N69 Roll command = -86.68 deg VL = 22091 ft/sec DL = 1.057g	VL_{max} = 22,400 ft/sec VL_{min} = 18,000 ft/sec DL_{max} = 1.54g DL_{min} = 0.84g	RTCC Values VL = 22024 ft/sec DL = 1.13g

Table III. The Chronological Sequence of Events of the Apollo 11 Entry and Available Pad Data Necessary to Monitoring Entry (Continued)

APOLLO 11 MISSION EVENT TIME	APOLLO 11 EVENT	REAL TIME DATA PROVIDED TO CREW	COMMENTS
EI + 2 min 06 sec	Actual time of VCIRC	PAD value of the time of VCIRC EI + 2 min 14 sec	
EI + 3 min 20 sec	Program 67 automatically sequenced in V06 - N66 DSKY DISPLAY; Bank Angle command = 0.0; Crossrange error = 11.0 n mi; Downrange error = -132.4 n mi		The target is south of the present flight plane and the predicted downrange is short of the target
EI + 3 min 28 sec	Max downrange error of -186.9 n mi short of target. Crossrange error is 3.74 n mi north of target		
EI + 3 min 46 sec	Time of the first non-zero roll command in final phase Bank angle command = 15.41 deg Downrange error = -23.5 n mi Crossrange error = -15.8 n mi north of the target		
EI + 6 min 04 sec	V16 - N67 DSKY DISPLAY RTOGO = -1.7 n mi Present latitude = -13.30 deg Present longitude = -169.15 deg		
EI + 9 min 13 sec	Drogues deploy	PAD value of drogue deploy was EI + 9 min 02 sec	

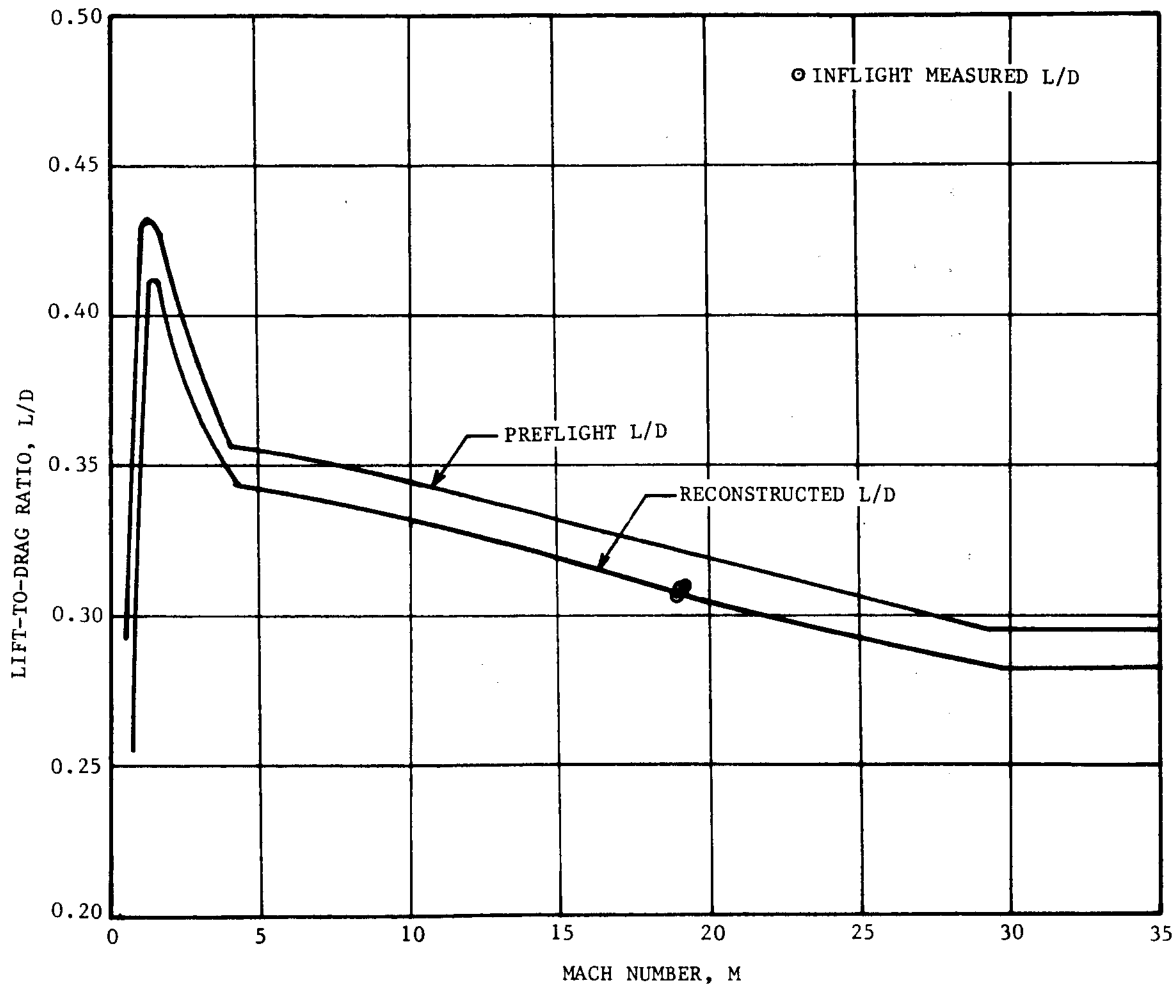

Figure 1. Apollo 11 Aerodynamic Data

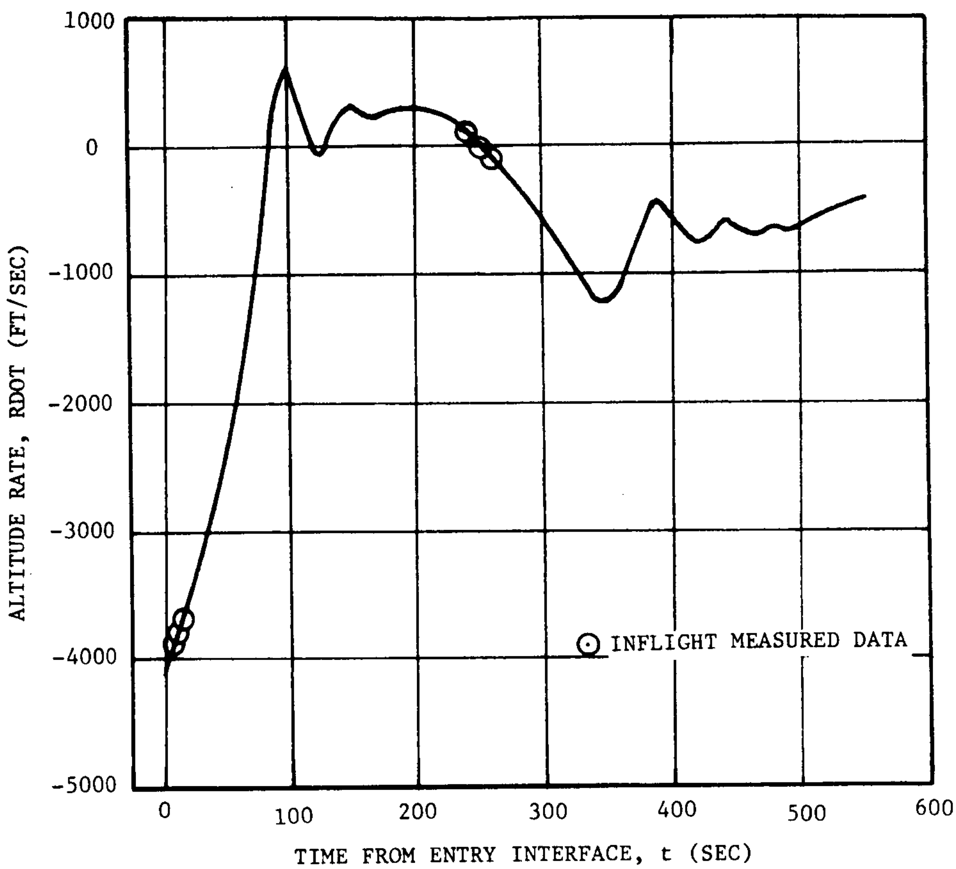

Figure 2. Time History of Altitude Rate from Reconstructed CMC

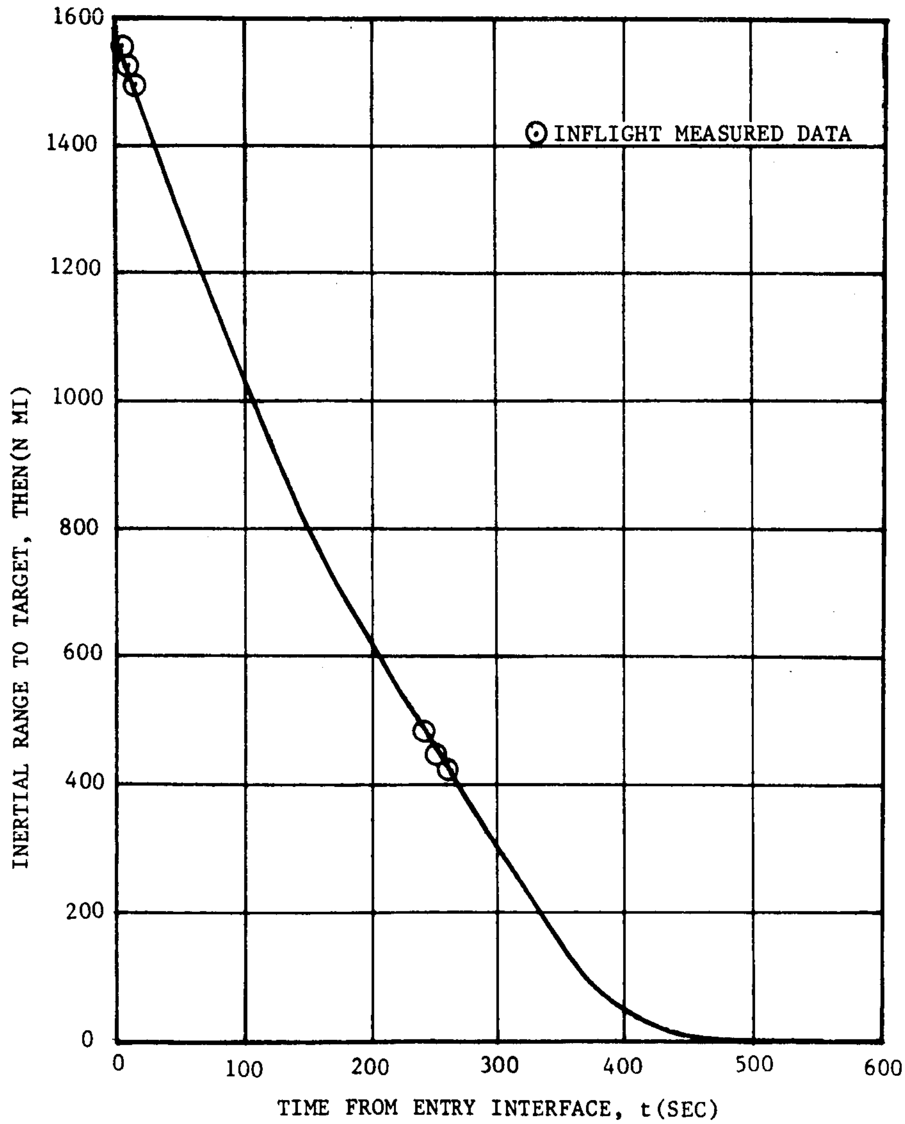

Figure 3. Time History of Inertial Range to Target from Reconstructed CMC

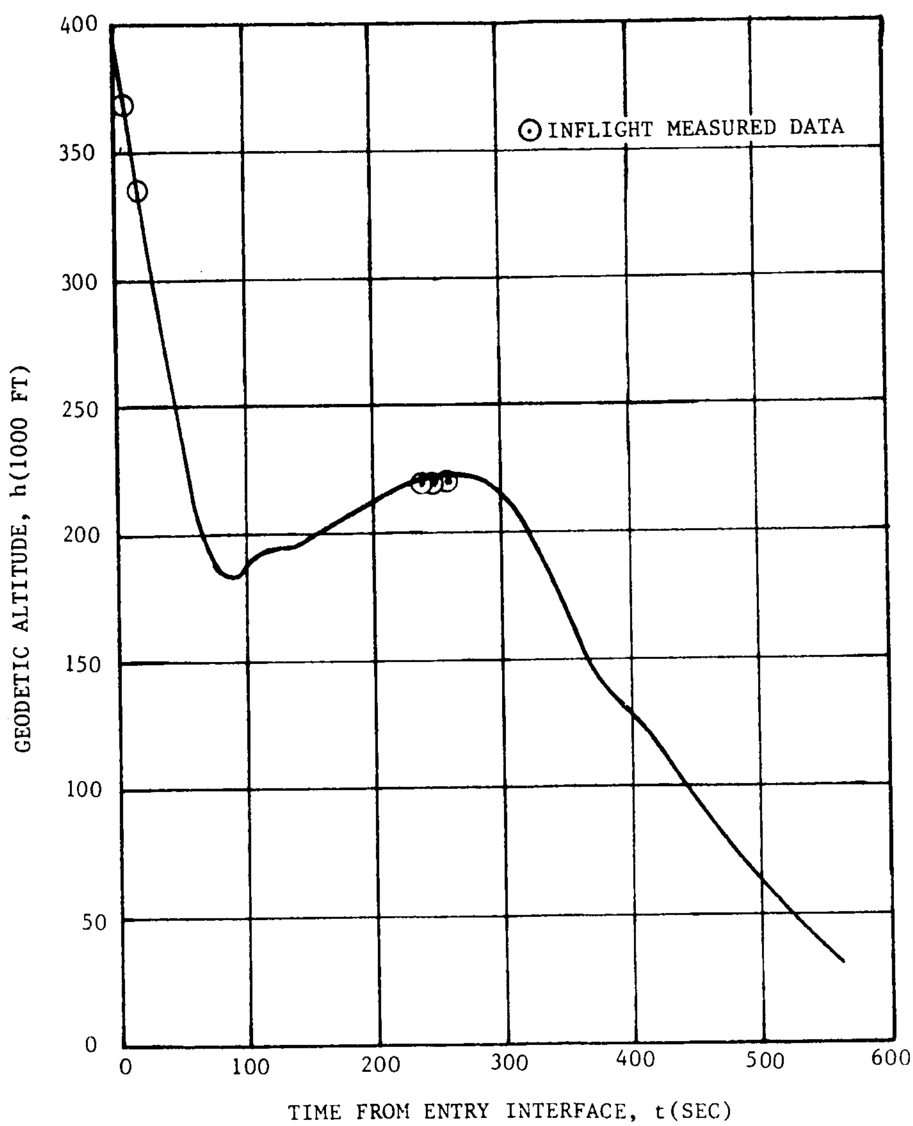

Figure 4. Time History of Altitude from Reconstructed CMC

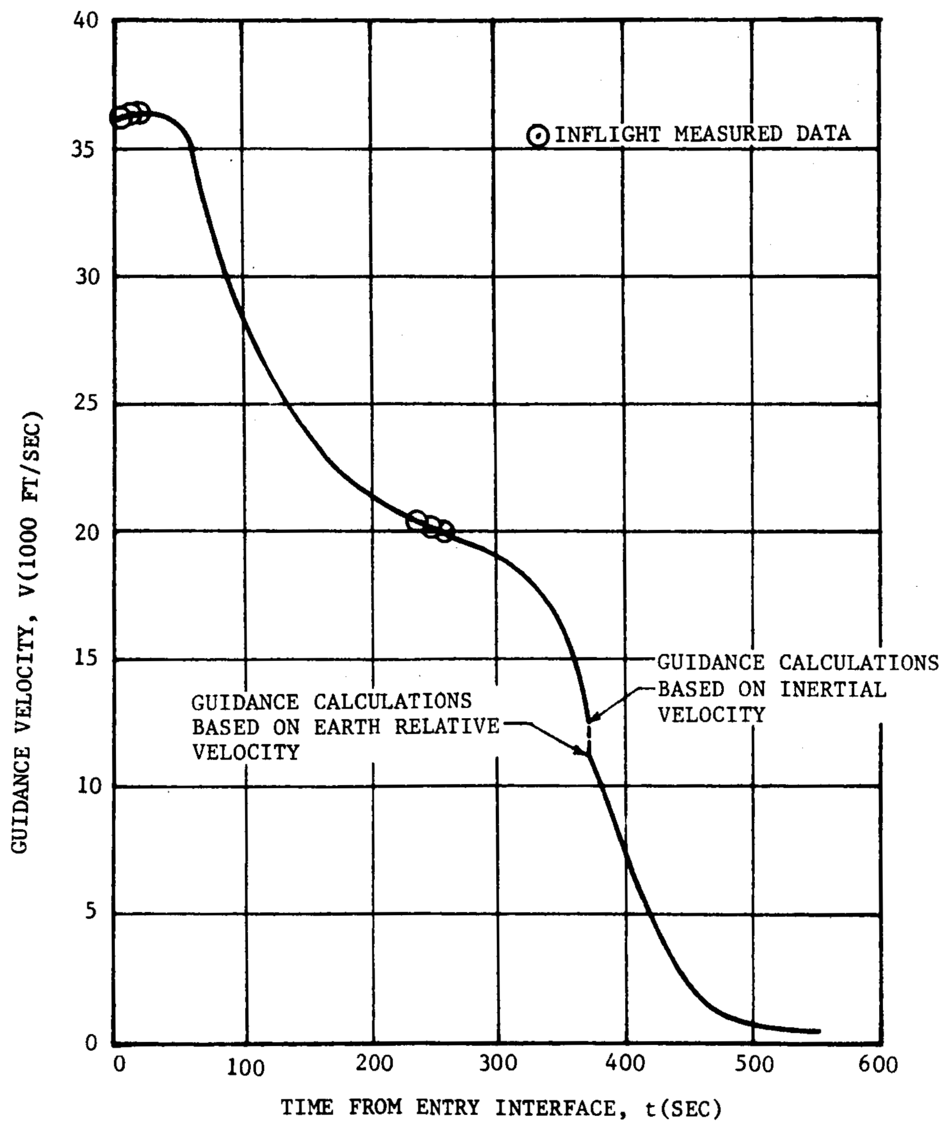

Figure 5. Time History of Guidance Velocity from Reconstructed CMC

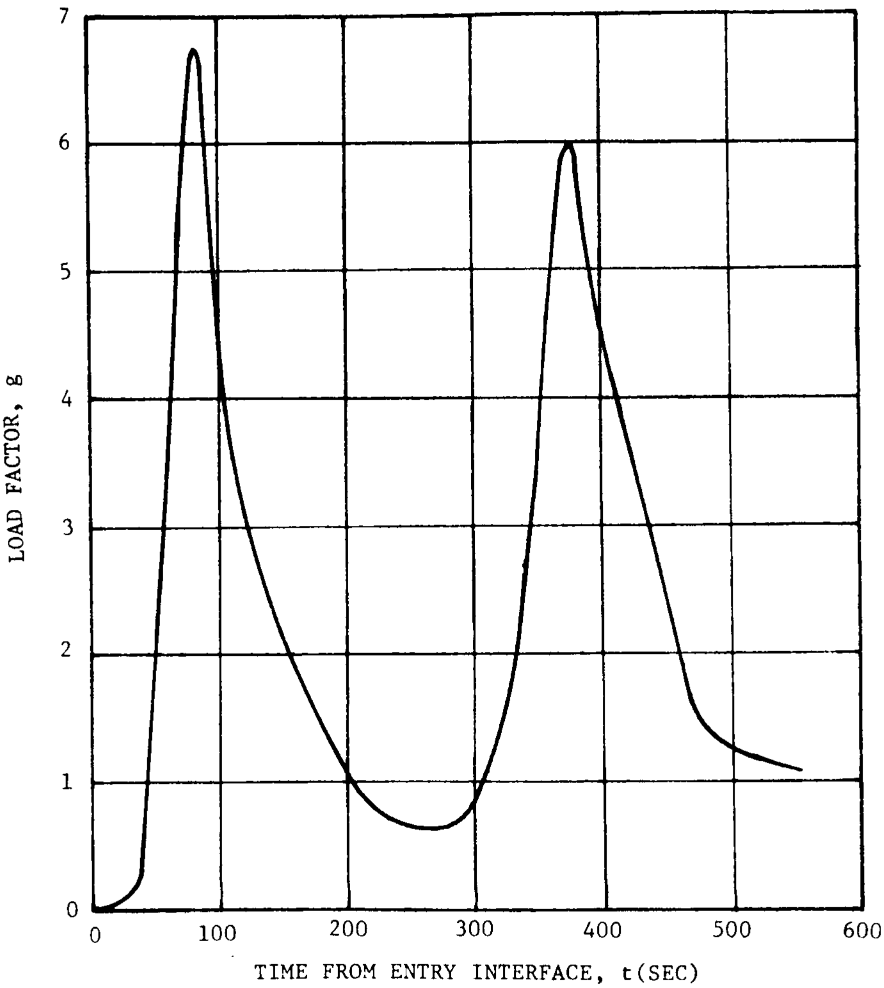

Figure 6. Time History of Load Factor from Reconstructed CMC

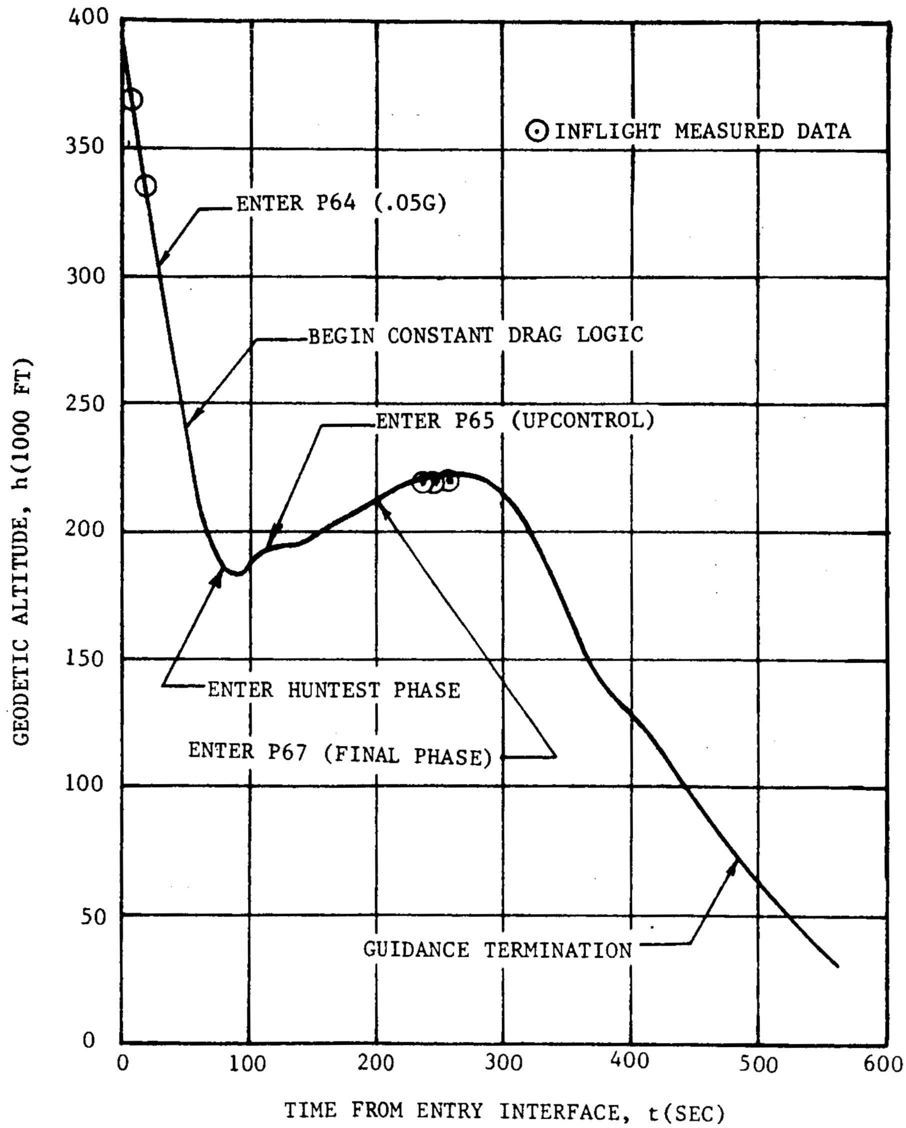

Figure 7. Reconstructed CMC Guidance Sequencing

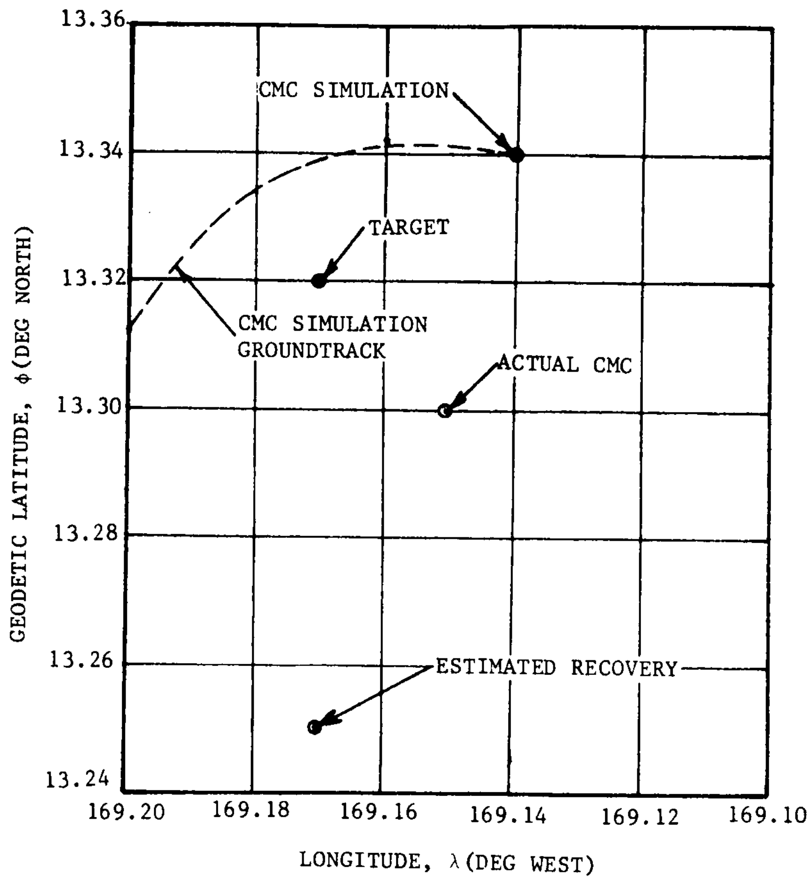

Figure 8. Apollo 11 Touchdown Coordinates

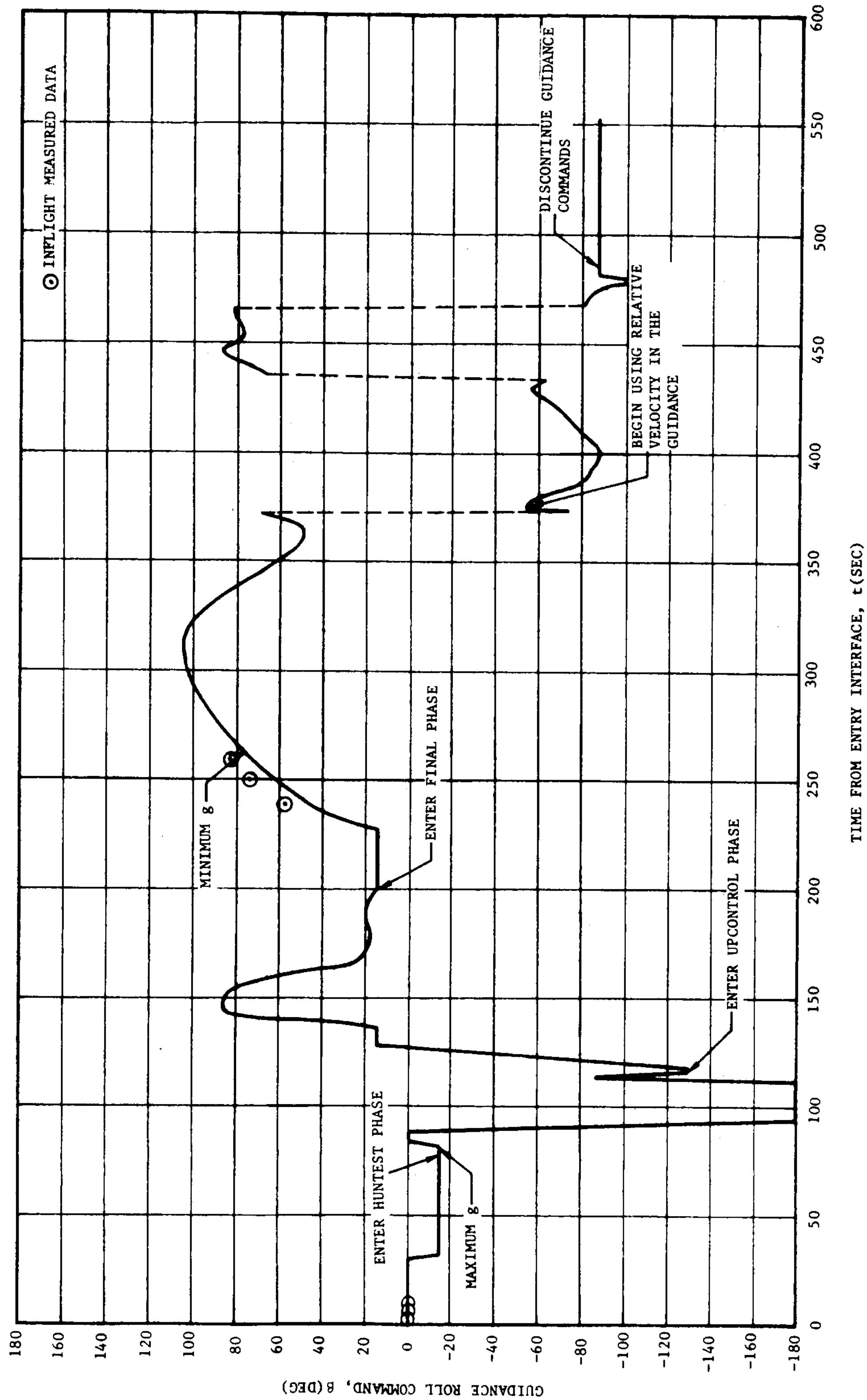

Figure 9. Time History of Guidance Roll Commands from Reconstructed CMC

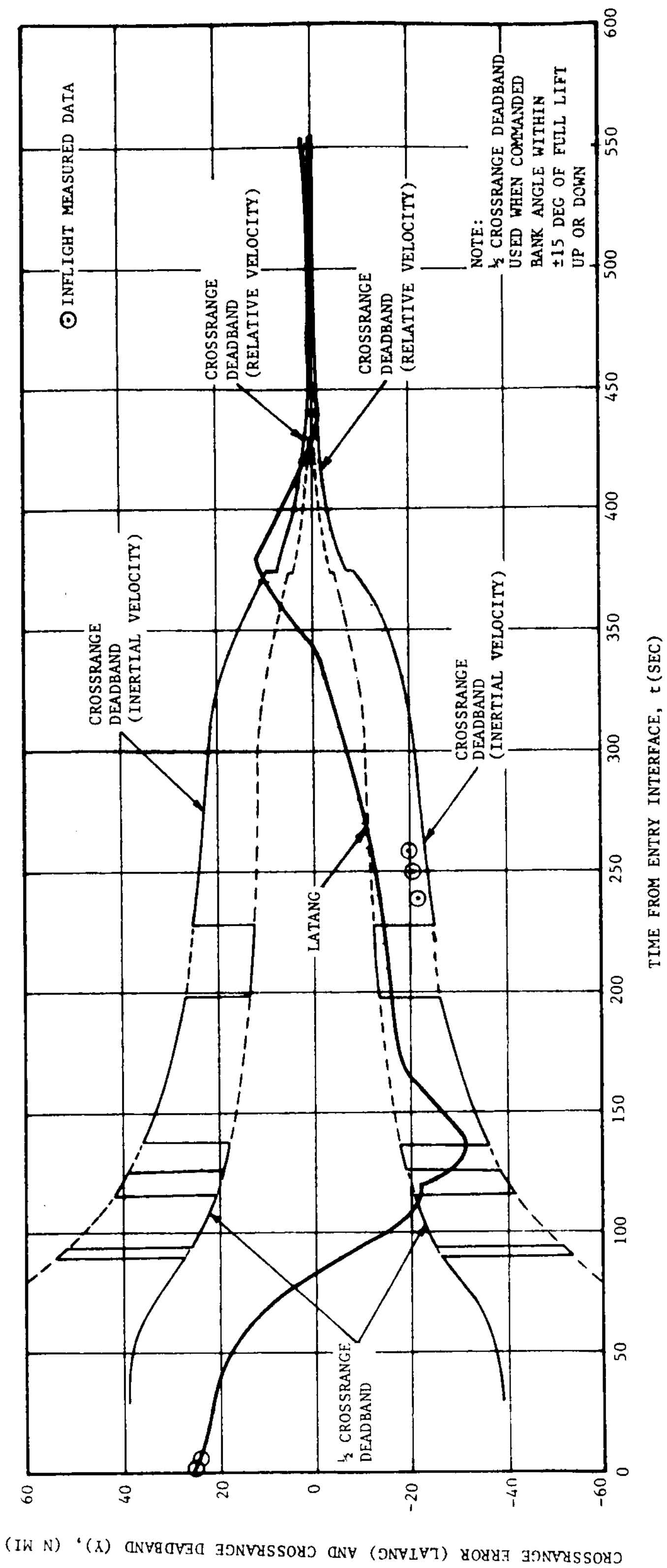

Figure 10. Time History of Crossrange Error and Crossrange Deadband Computed by Reconstructed CMC

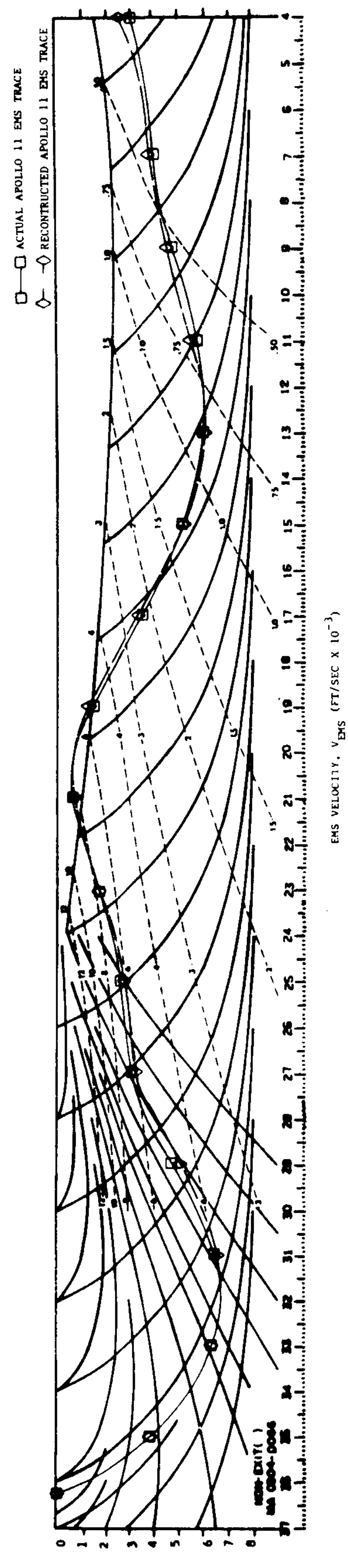

Figure 11. Comparison of Actual and Reconstructed EMS Trace for Apollo 11

	M	I	D	P	A	C	AREA
	X	X	X	0	0	0	R .05G
	X	X	X	1	5	2	P .05G
	X	X	X	0	0	1	Y .05G
1	9	4	4	6	0	6	GET HOR
	X	X	X	2	6	7	P CK
	+	0	1	3	3	2	LAT N61
	-	1	6	9	1	7	LONG
	X	X	X	0	6	3	MAX G
	+	3	6	1	9	4	V_{400K} N60
	-	0	0	6	4	8	γ_{400K}
	+	1	4	0	3	3	RTGO EMS
	+	3	6	2	7	5	V10
1	9	5	0	3	0	6	RRT
	X	X	0	0	2	8	RET .05G*
	+	0	0	1	5	4	D_L MAX* N69
	+	0	0	0	8	4	D_L MIN*
	+	2	2	4	0	0	V_L MAX*
	+	1	8	0	0	0	V_L MIN*
	X	X	X	4	0	0	D_0
	X	X	0	2	1	4	RET V_{CIRC}
	X	X	0	0	1	7	RETBBO
	X	X	0	3	5	1	RETEBO
	X	X	0	9	0	2	RETDRO
	X	X	X	X	4	5	SXTS
	+	0	1	8	9	0	SFT
	+	2	7	7	0	0	TRN
	X	X	X				BSS
	X	X					SPA
	X	X	X				SXP
	X	X	X	X	U	P	LIFT VECTOR

Figure 12. Final Entry Pad for Apollo 11

REFERENCES

1. Task Order for Apollo Lunar Exploration Program Entry Support. MSC/TRW Task No. A-220, Amendment No. 3, 1 January 1970.

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3. Cole, A. E. and Kantor, A. J.: Air Force Interim Supplemental Atmospheres to 90 Kilometers. Report No. 153, AFCRL-63-936, December 1963.